CONFERENCE OF THE COMMITTEE ON DISARMAMENT

CCD/363
25 April 1972
Original: ENGLISH

UNITED KINGDOM

Working paper on seismic yields of underground explosions - estimating yields of underground explosions from amplitudes of seismic signals

Definition of Yield and Magnitude

By making seismic measurements close to an explosion in a previously calibrated area, the energy release (size) of the explosion can be estimated. Such estimates of explosion size are generally referred to as the "seismic" yield of the explosion and are expressed in terms of kilotons. Recent testimony before the United States Joint Committee of the AEC suggests that yields of nuclear explosions in the Nevada Test Site can be estimated from such measurements to within 15 to 20 per cent of the yields estimated from radiochemical measurements.

In the context of the comprehensive nuclear test ban (CTB) discussions, the Conference of the Committee on Disarmament (CCD) has been concerned with the more difficult problem of estimating yields of nuclear explosions from seismic waves which have traversed uncalibrated paths of much greater length. A brief recapitulation of the principles involved may be convenient. A small part of the energy released by underground explosions is converted to elastic energy and transmitted to distant parts of the earth as seismic waves. From the amplitudes of these waves, seismologists can determine a "seismic magnitude" for the explosion using magnitude scales devised to measure the relative size of earthquakes. The amplitudes of the seismic waves cannot be used directly as a measure of the size of a seismic event because the recorded amplitude depends on the distance of the recording station from the explosion: in general, the greater the distance the smaller the recorded signal. In computing the magnitude, a factor is applied to the recorded amplitude to correct for the effects of

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distance, after which all recording stations ideally give the same magnitude for a given event regardless of distance from the source of the event.

In this working paper we discuss the relationship between the seismic magnitude scales and explosion yields and demonstrate some of the difficulties in arriving at a consistent relationship, and hence in relating the detection and identification thresholds, expressed as magnitudes, of a given recording system to explosion yields.

When the CTB discussions began in 1958 the problem of estimating the relative sizes of earthquakes from recordings at distant stations already had a long history of careful experimental work. The principal objective of the research was the provision of universal distance factors and the following section summarizes the development of this work.

The Seismic Magnitude Scales

A scale for measuring the relative sizes of earthquakes was initiated by Dr. Charles Richter at the Californian Institute of Technology some 40 years ago. A local scale was developed for use with events within 600 kilometres of recording stations, particularly in California, in order to eliminate subjective assessments of size by affected populations. The seismic magnitude scale is logarithmic, that is, differences in amplitudes of 10 at a given station from events at similar distances represent differences of one magnitude unit in the size of the events; the larger the number the greater is the size of the event.

Richter's scale turned out to be more successful than had been expected, and attempts were made to extend its usefulness beyond the local seismic problems of California. With Dr. B. Gutenberg, Richter attempted the task using the combined surface waves recorded by two horizontal components. (In those days, sensitive vertical component seismographs could not be built because of technical problems concerned with the length and stability of springs). This still left out deep focus earthquakes which do not generate such large surface waves, so Gutenberg went a step

further and created a magnitude scale based on the amplitudes of long period (low frequency) body waves, including, of course, the first arriving P waves. The results of this work were published in 1945. Finally, in 1956, Gutenberg and Richter published what is called the unified scale which makes use of data from all sources, including short period P waves. The authors used the term m_b to identify unified magnitudes, and it is this scale which has been in common use for CTB discussions since 1958 because for distant events more data for short period than for long period P waves have been available from the Benioff and Willmore vertical component seismographs. In recent years, however, surface (Rayleigh) wave data have been provided by more sensitive long period vertical component seismographs. The value of magnitudes (Ms) derived from them for discriminating between explosions and earthquakes is well known. This paper demonstrates that surface waves are also useful for estimating the yield of explosions.

Data from small events located at great distances were not numerous in the early days of CTB discussions and the various problems arising in these discussions focussed attention much more than before on the relative sizes and numbers of small seismic events. The problem of relating the original magnitude scale for local events (which included a sufficient number of small earthquakes) to the unified scale (which did not) proved difficult to solve during the lifetime of Technical Working Group II at Geneva in 1959. Long period instruments sensitive enough to record surface waves of such small events had not been developed at the time, and the Kirnos instruments of the Soviet Union, though technically ideal for resolving inconsistencies in the body wave magnitude scales, detect only the larger distant events above the seismic noise which is also well recorded by these seismographs. Some of the early difficulties encountered in applying the unified, or as it is now called, the m_b scale to the detailed seismological problems of a CTB remain unresolved insofar as international agreement is concerned, and an Appendix is devoted to the problem in the report of the Conference on Seismic Methods for Monitoring Underground Explosions, SIPRI Stockholm, 1968.

Specific examples of the problem insofar as it relates to estimating seismic yield of explosions are provided below. They are selected (a) from the United Kingdom studies, on the well documented explosions codenamed Gasbuggy, Rulison and Medeo, which were circulated by the United Kingdom Delegation to the CCD in August 1970 and (b) from the explosions on Amchitka Island in the Aleutians, two of which are equally well documented (for example in AWRE Reports O-67/66 of October 1966, and O-47/70 of August 1970), and which provide a useful frame of reference over a wider range of yields. No attempt is made to summarize the whole of the m_b -- Yield data which has accumulated since 1958; this is the subject of a detailed analysis which is being prepared for publication.

The curve which accompanies this paper (Annex A) does, however, summarize the more consistent surface wave magnitude (M_s) -- yield data. The M_s values plotted on this curve have been measured in accordance with the recommendations outlined in the Canadian Working Paper CCD/327 of June 1971, and detailed in a technical paper soon to be published in the Geophysical Journal of the Royal Astronomical Society, London. Some of the data on which the M_s -- yield curve is based are presented in the technical paper (Nature 1971 Vol.234, pp. 8-9) at Annex B.

m_b - Yield

Commonsense would suggest that m_b values should increase with increasing explosion yield. This idea can be demonstrated experimentally when source to receiver paths are identical, or nearly so, for successive explosions. Take for example the three explosions on Amchitka Island in the Aleutians as recorded at Eskdalemuir in Scotland. (Yield and magnitude values are rounded off to the nearest significant figure in all the following tables).

Table of Yields and Magnitudes for Explosions on Amchitka Island Recorded at Eskdalemuir

Explosion	Yield (kilotons)	Yield Ratio	Relative Size from Seismic Amplitudes at Eskdalemuir	Seismic Magnitude at Eskdalemuir (m_b)
Longshot	100	1	1	6.2
Milrow	1000	10	2½	6.6
Cannikin	5000	50	5	6.9

It might also be expected that the seismic amplitudes would increase in the same ratio as the yields, but this is manifestly not true for the Amchitka to Eskdalemuir path for the observed range of yields.

Nevertheless the result fulfils expectations more closely than the following example of two explosions separated by 300 km on the same continent, which were also recorded at Eskdalemuir.

Table of Yields and Magnitudes for Gasbuggy and Rulison Recorded at Eskdalemuir

Explosion	Yield (kilotons)	Yield Ratio	Relative Size from Seismic Amplitudes at Eskdalemuir (Corrected for distance)	Seismic Magnitude at Eskdalemuir (m_b)
Gasbuggy (New Mexico)	26	1	1 (4)	5.3
Rulison (Colorado)	40	1½	0.25 (1)	4.7

On the face of it, the smaller explosion has given the larger seismic signal. A special study by the United Kingdom of the signal amplitudes recorded by distant (teleseismic) stations and omitting the close-in stations of North America, confirms that the result is not a peculiarity of Eskdalemuir: the average figures are, for Gasbuggy, m_b 5.0 and for Rulison m_b 4.9.

The next example is even more remarkable. It compares readings at Eskdalemuir of Rulison in the United States with two chemical explosions (Medeo) in the Alma Ata region of the Soviet Union.

Table of Yields and Magnitudes for Rulison and Medeo Recorded at Eskdalemuir

Explosion	Yield (kilotons)	Yield Ratio	Relative Size from Seismic Amplitudes at Eskdalemuir (Corrected for distance)	Seismic Magnitude at Eskdalemuir (m_b)
Rulison	40	24	1	4.7
Medeo (1) (Chemical)	1.7	1	2	5.0
Medeo (2)	3.6	2	3	5.2

The relative size of Medeo (1) as estimated from seismic amplitudes was double that of the explosion which was 24 times more powerful.

These are well documented and accurately made observations which cannot be disputed. Since they were made in the real world, the observations must have rational explanations. The explanations, however, are in dispute and have been the subject of much debate in recent years. Some possible explanations are listed in the following paragraphs, but no attempt is made to arrive at degrees of plausibility or priority, nor to make detailed quantitative assessments. These topics are being dealt with at length in the detailed study referred to earlier.

Discussion of m_b - Yield Anomalies

Along with most seismograph systems Eskdalemuir was designed to detect the characteristic band of frequencies in which the seismic energy of small events is radiated. The centre point of this band moves towards lower frequencies as the size of explosions increases, and because for an explosion of one megaton the centre point of the radiated energy lies on a different part of the sensitivity curve than for one of 1 kiloton, the recorded amplitudes may be that much smaller. (The analogy of radiation from the sun is opposite: the human eye cannot perceive beyond the ultra violet and infra-red ends of the light spectrum.) The importance of the effect for estimating magnitude (m_b) of explosions may be uncertain, but its effect in assessing the relative sizes of larger earthquakes is obvious when comparing the m_b values of "standard" (WWSSN) stations with those of the wide band Kirnos instruments of the Soviet Union. The Kirnoc also records a great deal of earth noise and has consequently been held to be less useful since the CTB discussion stimulated efforts for the detection of ever smaller events and thereby pushed research teams into recording two narrow samples of the total seismic spectrum. Nowadays there is a much greater understanding of the structure of earth noise, and the means for reducing its effects, and a new look might with advantage be taken at the Kirnos type system, for discrimination problems as well as those of magnitude and yield.

Another source of the observed anomalies may be due to differences in coupling efficiency. The Committee is already aware that media in which nuclear explosives are emplaced can affect the size of the P wave signals by factors of ten or more when comparing coupling efficiency in dry alluvium with that of a massive rock like granite. In the case of Gasbuggy and Rulison the rocks are shale and sandstone (see AWRE Report O-46/70), which though very different types of rock, are seismically not so different from each other as are dry alluvium and granite. The Medeo explosions were designed to move earth rather than generate seismic energy, and were therefore

incompletely contained; and though that gives the results an even more extraordinary aspect, it must be said that the more slowly reacting chemical explosions are more efficient generators of seismic energy than are nuclear explosions; only a factor of about 2 or 3 has ever been suggested, however.

The amplitude of short period P waves is also sensitive to source depth. The depths at which Gasbuggy (1,300 metres) and Rulison (2,574 metres) were buried are unusually large for the yields involved because the experiments were designed for the purpose of improving the flow of natural gas in strata at those depths. (For weapon tests, it is necessary to bury the device only to a depth sufficient for containment of radioactive debris.) This depth would have the effect of increasing the seismic coupling efficiency, but would tend to separate the surface reflected signal away from the direct signal. This would be particularly true of Rulison, for which the surface reflection can be clearly observed arriving some $1\frac{1}{2}$ seconds after the direct P wave at Eskdalemuir (Figures 2 and 3, AWRE Report O-46/70). In the case of Gasbuggy (and all nuclear weapon tests of similar size which were buried at shallower depths) the surface reflection adds to the direct signal and can thereby double the amplitude of the direct signal. The yields of weapons such as Milrow and Cannikin, however, are so large that the depths for full containment of the debris are sufficient to separate the reflected and direct signals, and the magnitudes of both these events may thereby be under-estimated relative to Longshot; factors nearer to 2 than to 10 are involved.

However, possibly the most important cause of m_b anomalies has been revealed in the last twelve months by studies in the United Kingdom, which indicate that there are deep seated geological structures, in areas which are associated with earthquake belts and with mountain ranges, having a greater capacity for absorbing high frequency seismic energy (short period P waves) than the ocean floor and those ancient blocks in the interior of continents known as shields. Such structures may also cause the

P wave radiation to take two or more paths (multi-pathing) just different enough to cause the signals to interfere one with the other at the recording stations. By means of computers, models of these possible structures have been designed and the passage of seismic signals in them have been studied. The results do suggest that the geophysical causes of the more extraordinary anomalies may be found to underlie seismic and recently seismic areas. As explosion seismologists develop techniques for using larger chemical explosions for the study of earth structure, more evidence accumulates to illustrate the effects because the detonations are often in stable, aseismic areas. The most recent example, an explosion of 10 tons in the North Sea, was reported in the journal Nature as having been recorded as far away as Brasilia and Brisbane, and was given a seismic magnitude of m_b 4.8 at Vinta Basin in Utah. The United Kingdom studies predict that explosions in continental shield areas recorded by stations on shields will be assigned m_b magnitudes some two units greater than recordings of the same yield on seismic area to seismic area paths. When the Soviet Union releases more yields of explosions, great progress in this field of research will be possible because of the variety of geologic structures and seismicity in that country.

But, whatever the explanation, the observations of m_b are a matter for concern since one conclusion to which they lead is that it is at present almost impossible to estimate the relative size of explosions from m_b unless they are fired at one site and compared at one station. This is a very serious constraint in the context of a CTB. Whether for counting numbers of earthquakes at a given yield equivalent, or for defining magnitude yield thresholds, a method for estimating the relative sizes of earthquakes and explosions, much less sensitive to source, path, and receiver and which provides for easily evaluated path corrections is highly desirable.

In recent years the United Kingdom has therefore devoted some effort to the study of this problem. The successful development of sensitive long period vertical seismographs by the United States has made possible the accumulation of surface wave data of small events. The principal impact of these data has, of course, been on the m_b : M_s criterion for discriminating between earthquakes and explosions but the United Kingdom has taken another look at the use of surface wave magnitudes (M_s) for estimating yield, and the principal results of this study are reviewed in the final paragraphs of this paper.

M_s - Yield

What has always been attractive about using surface waves for estimating relative size is firstly, that the much larger wavelengths make them less sensitive to the vagaries of geologic structure, so that gross path corrections can be applied on a continent wide basis, (as was amply demonstrated in the Canadian Working Paper) and secondly, that the frequencies of the recorded signals fall within the usual recording band of frequencies of long period seismographs over a much greater range of yield than is the case for the P signals recorded by high gain short period seismographs. Surface wave magnitudes are also preferred because seismographs in the Soviet Union provide almost identical M_s values to those estimated elsewhere. The difficulty in the use of M_s has been that surface waves were recorded only from relatively large events.

The following table gives the surface wave magnitude-yield comparisons for the set of explosions which have been looked at earlier when considering the m_b - yield relationship. The Medeo explosions cannot be included because no surface waves from them have been detected outside the Soviet Union. The surface wave magnitudes have been determined in accordance with the recommendations of the Canadian Working Paper CCD/327.

Table of Yields and Magnitudes (M_s) for Underground Explosions in the United States

Explosion	Yield (kilotons)	Yield ratio	Relative size from seismic amplitudes (corrected for distance and path according to CCD/327)	Average seismic magnitude (M_s)
Gasbuggy	26	1	1	3.4
Rulison	40	1½	1.6	3.6
Longshot	100	4	5	4.1
Milrow	1 000	40	60	5.2
Cannikin	5 000	200	200	5.7

It is immediately obvious that the M_s values are much more consistent over the whole range of yields than any of the m_b values listed in the earlier tables, not only in relation to yield, but also from site to site. This very satisfactory result has been confirmed by detailed analysis of all the surface wave data available to the United Kingdom from explosions for which the yields have been announced, by France, the Soviet Union and the United States.

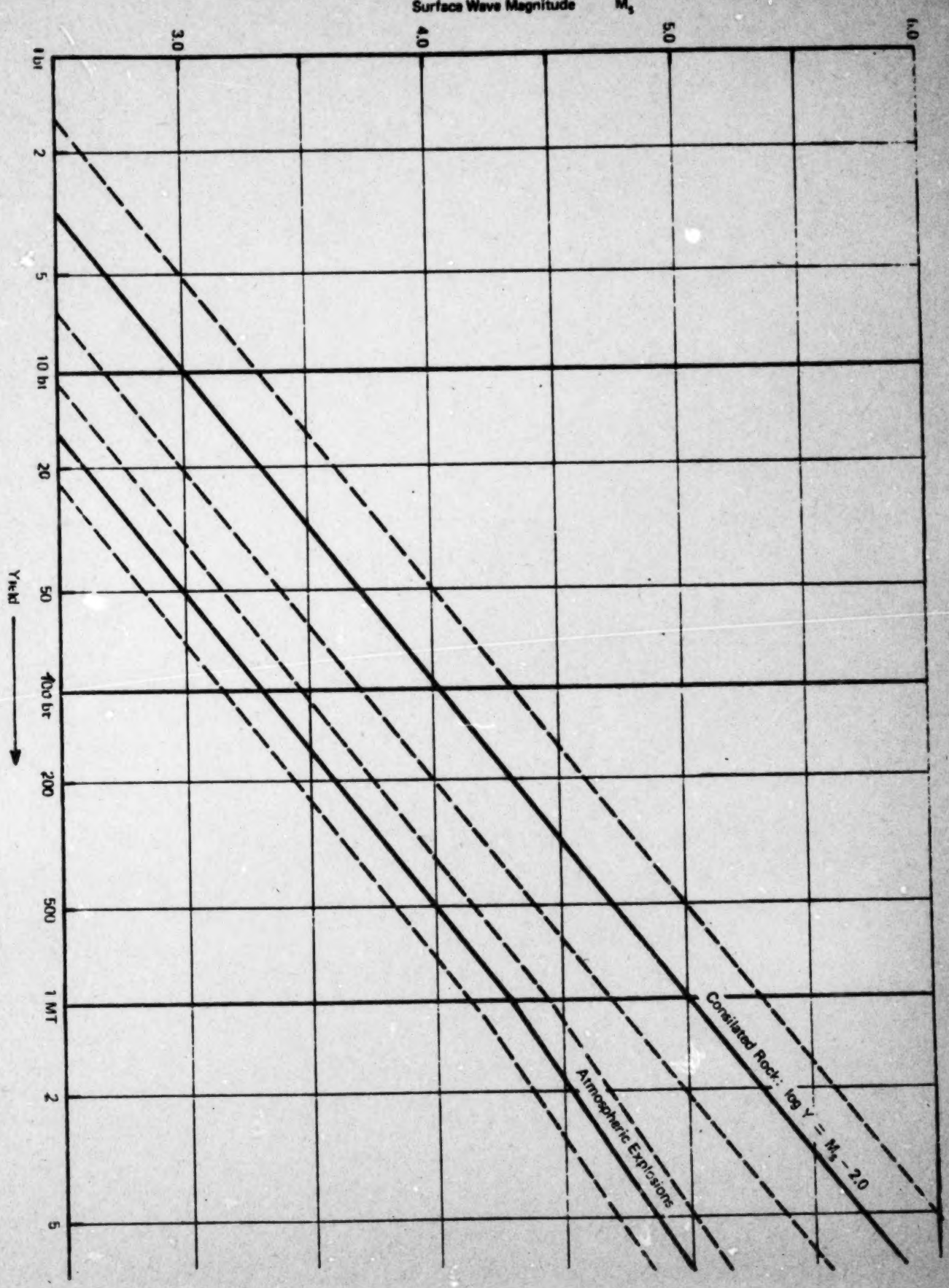
The attached curve at Annex A summarizes the analysis. For completeness, the M_s - yield theoretical curve for atmospheric explosions is also summarized. The theoretical basis for the curve was published in AWRE O-88/70 of November 1970 and is of special interest at lower yields (less than 50 kilotons) because it applies also to underground explosions in dry alluvium or other unconsolidated rocks. The curve for underground explosions applies to containment in any consolidated rock, in any part of the world. The dotted lines, which bracket the solid, show the maximum scatter of the observations used in the analysis. The release of more yield data, together with more refined path corrections is expected to decrease the width of the error bands.

These curves are now used by the United Kingdom for obtaining the best estimates of seismic yield. Low yield explosions, for which surface waves are not detected, must still be estimated from m_b with all their inherent uncertainties, but explosions as small as 5 kilotons have provided surface waves records from the closer stations. As more surface wave data are released, and better long period stations are deployed, the limit of the method will be established, and this limit is also of interest as representing the technical threshold for discrimination by the m_b:M_s criterion.

In using the curves, delegations may find it interesting to make estimates of yield from M_s values provided by their national stations or by world data centres. The path corrections will be found in the technical paper on which the Canadian working paper CCD/327 is based. As an example on which to conclude, the following estimates of the yields of some of the larger underground explosions, which have occurred at each of the world's principal nuclear test sites, are estimated from the path corrected world average M_s values, and the recommended M_s - yield relationship.

Site	Explosion	Average, path corrected M_s	Yield estimates from curve, or $\log Y = M_s - 2$ (kiloton)
Sahara	Saphir	4.1	125
Kazakh	13 February 1966	4.4	250
Nevada	Greeley	5.1	1 250
Nevada	Benham	5.1	1 250
Novaya Zemlya	14 October 1970	5.1	1 250
Novaya Zemlya	27 September 1971	5.1	1 250
Aleutian Is	Milrow	5.2	1 600
Aleutian Is	Cannikin	5.7	5 000

Surface wave magnitude-yield curve



(Reprinted from Nature, Vol.234, No.5323, pp. 8-9, November 5, 1971)

SURFACE WAVES FROM UNDERGROUND EXPLOSIONS

Several authors[1,2] have published data on the surface wave magnitude (M_s) and yield (Y) for underground explosions at test sites in North America. Fig. 1 shows the dependence of M_s on yield for all test sites for which we could obtain explosion yield data. The details of the explosions are given in Table 1. From Fig. 1 it is clear that for explosions in consolidated rock (tuff, salt, granite, andesite and sandstone) all the observations lie close to the line

$$M_s = \log Y + 2.0$$

for yields from 4 kton to 1,300 kton. Only for Discus Thrower and Duryea does the observed value of M_s deviate by more than 0.3 magnitude units from this line, so only for these explosions would the yield estimated from M_s differ by more than a factor of 2 from the published yield. For explosions in unconsolidated rock (alluvium) the curve of M_s against yield seems to be more like

$$M_s = \log Y + 1.0$$

at least for yields less than 100 kton, but more data are required to define this curve. The M_s values plotted in Fig. 1 are means of individual station determinations of M_s, each of which is corrected for deviations of the source to receiver path from an

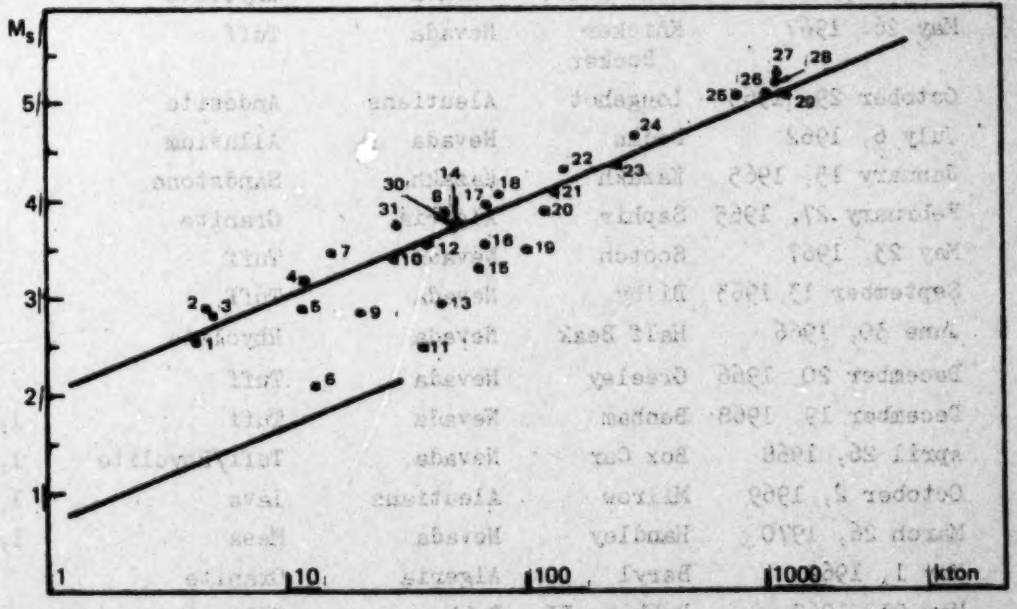


Fig. 1 Surface wave magnitude (M_s) against yield (kton) for explosions in various parts of the world.

Table 1 Details of Some Underground Explosions

Event No.	Date	Name	Region	Medium	Yield(kton)
1	April 14, 1965	Palanquin	Nevada	Rhyolite	4.3 a/
2	February 15, 1962	Hardhat	Nevada	Granite	4.8 a/
3	October 22, 1964	Salmon	Mississippi	Salt	5.3 a/
4	October 26, 1963	Shoal	Nevada	Granite	12.2 a/
5	November 5, 1964	Handcar	Nevada	Dolomite	12 a/
6	December 3, 1961	Fisher	Nevada	Alluvium	13.5 a/
7	February 24, 1966	Rex	Nevada	Tuff	16 a/
8	September 30, 1966	Bukhara I	Bukhara	Clay	30 f/
9	May 27, 1966	Discus Thrower	Nevada	Tuff	21 d/
10	December 10, 1967	Gasbuggy	New Mexico	Shale	29 a/
11	October 9, 1964	Par	Nevada	Alluvium	38 a/
12	September 10, 1969	Rulison	Colorado	Shale	40 a/
13	June 27, 1962	Haymaker	Nevada	Alluvium	45.5 a/
14	June 2, 1966	Piledriver	Nevada	Granite	56 a/
15	April 14, 1966	Duryea	Nevada	Rhyolite	65 a/
16	May 6, 1966	Chartreuse	Nevada	Rhyolite	70 a/
17	May 26, 1967	Knicker Bocker	Nevada	Tuff	71 a/
18	October 29, 1965	Longshot	Aleutians	Andesite	85 a/
19	July 6, 1962	Sedan	Nevada	Alluvium	100 b/
20	January 15, 1965	Kazakh	Kazakh	Sandstone	125 g/
21	February 27, 1965	Saphir	Algeria	Granite	135 d/
22	May 23, 1967	Scotch	Nevada	Tuff	150 a/
23	September 13, 1963	Bilby	Nevada	Tuff	250 a/
24	June 30, 1966	Half Beak	Nevada	Rhyolite	300 a/
25	December 20, 1966	Greeley	Nevada	Tuff	825 a/
26	December 19, 1968	Benham	Nevada	Tuff	1,100 a/
27	April 26, 1968	Box Car	Nevada	Tuff/Rhyolite	1,200 a/
28	October 2, 1969	Milrow	Aleutians	Lava	1,200 e/
29	March 26, 1970	Handley	Nevada	Mesa	1,200 e/
30	May 1, 1962	Beryl	Algeria	Granite	52 g/
31	May 21, 1968	Bukhara II	Bukhara	Salt	47 f/

a/ Ref.10; b/ Vela "Uniform" Information Digest, 2 No.11; c/ inferred from New Scientist, May 19, 437 (1966) and ref.13; d/ ref. 9; e/ press reports; f/ inferred from press reports and ref.11; g/ ref.12.

average path. After correction, the standard deviation (SD) of an observation for a given explosion is usually 0.25 magnitude units and the SD on the mean value of M_s is about 0.1. Corrections are applied for the effect of the path on the propagation of surface waves of different periods. Over short paths in North America, for example, the large amplitude pulse-like arrival observed on wide-band long-period instruments is made up of period components close to a minimum value in the group velocity curve. This apparent large amplitude is due to the path and not to the source; the path effect can be estimated as a function of frequency and a correction determined (P.D.M. and P. Basham, to be published). It should be pointed out that path corrections are significant only for short transmission paths over which there is little dispersion. If these transmission path corrections are not applied, the data do not display a consistent relationship between M_s and yield when data from different test sites are combined.

Theoretical curves of M_s against yield computed using the theory described by Hudson[3,4] and using the explosion source functions of Haskell[5] are also shown in Fig.1. These theoretical computations have also been corrected to an average crust. For consolidated rocks, the fit of the computed curve with the observations is very good; for unconsolidated rocks the predicted value of M_s for a given yield seems to be rather low. (Theoretical predictions were only made up to 30 kton in unconsolidated rocks because this is approximately the maximum yield for containment in a surface layer of alluvium 0.5 km thick - the depth of the alluvium layer in the crustal model of the Nevada Test Site[8]).

From the data presented in Fig. 1 we conclude that, provided one assumes that explosions at any location have been fired in consolidated rock, yields can usually be estimated to within a factor of two. This is a great improvement on routine calculations using body wave magnitude. For example, the body wave magnitudes (m_b) of the MEDEO explosions (1.6 kton and 3.7 kton chemical explosions) were 5.0 and 5.2 respectively at Eskdalemuir (EKA)[7] whereas the value of m_b for the 40 kton Rulison explosion in Colorado was found to be 4.7 at EKA[8]. Fig. 1 also shows that the use of the m_b:M_s criterion[9] to identify explosions at the teleseismic detection limit of $M_s \sim 2.5$ implied yields of about 40 kton in dry alluvium and 3 kton in consolidated rock. Long period arrays on low noise sites are required to record such low magnitudes at distances greater than 15 degrees from the firing site.

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Received 2 November 1971.

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